Turbulence forecasting for boundary layer turbulence

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Aviation turbulence forecasting

- Goal: Provide operationally useful nowcasts and forecasts of turbulence that is readily available to the aviation community
  - 24 x 7
  - Easy to understand graphical displays
  - Forecasts out at least 6 hrs over US, 12 hrs globally
  - All flight levels from surface to 45,000 ft (~13.7)
  - Meets some minimum statistical performance requirements
  - Focus has been on upper-levels where commercial aircraft are in cruise and passengers/flight attendants are often unbuckled

- But character of upper-level turbulence is different than low-level (boundary layer) turbulence so forecasting strategies (esp. for UAVs) must account for this

A turbulence diagnostic/forecasting system must account for all sources of turbulence

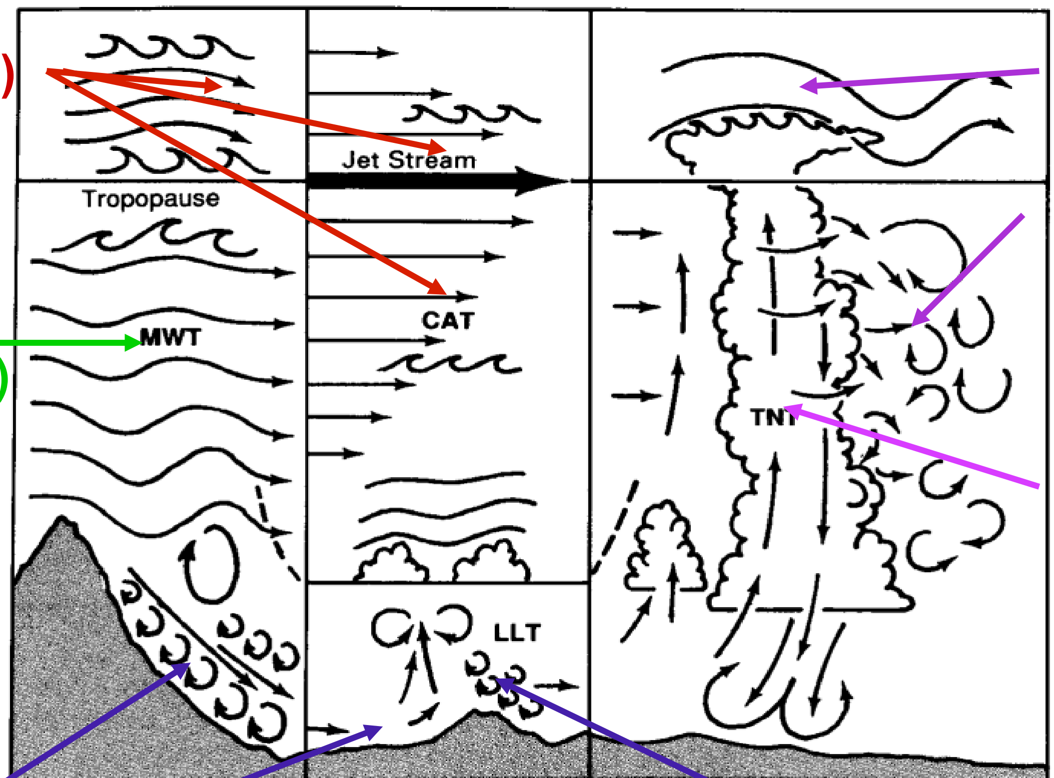

Figure 1-16. Aviation turbulence classifications. This figure is a pictorial summary of the turbulence-producing phenomena that may occur in each turbulence classification.

Source: P. Lester, "Turbulence – A new perspective for pilots," Jeppesen, 1994

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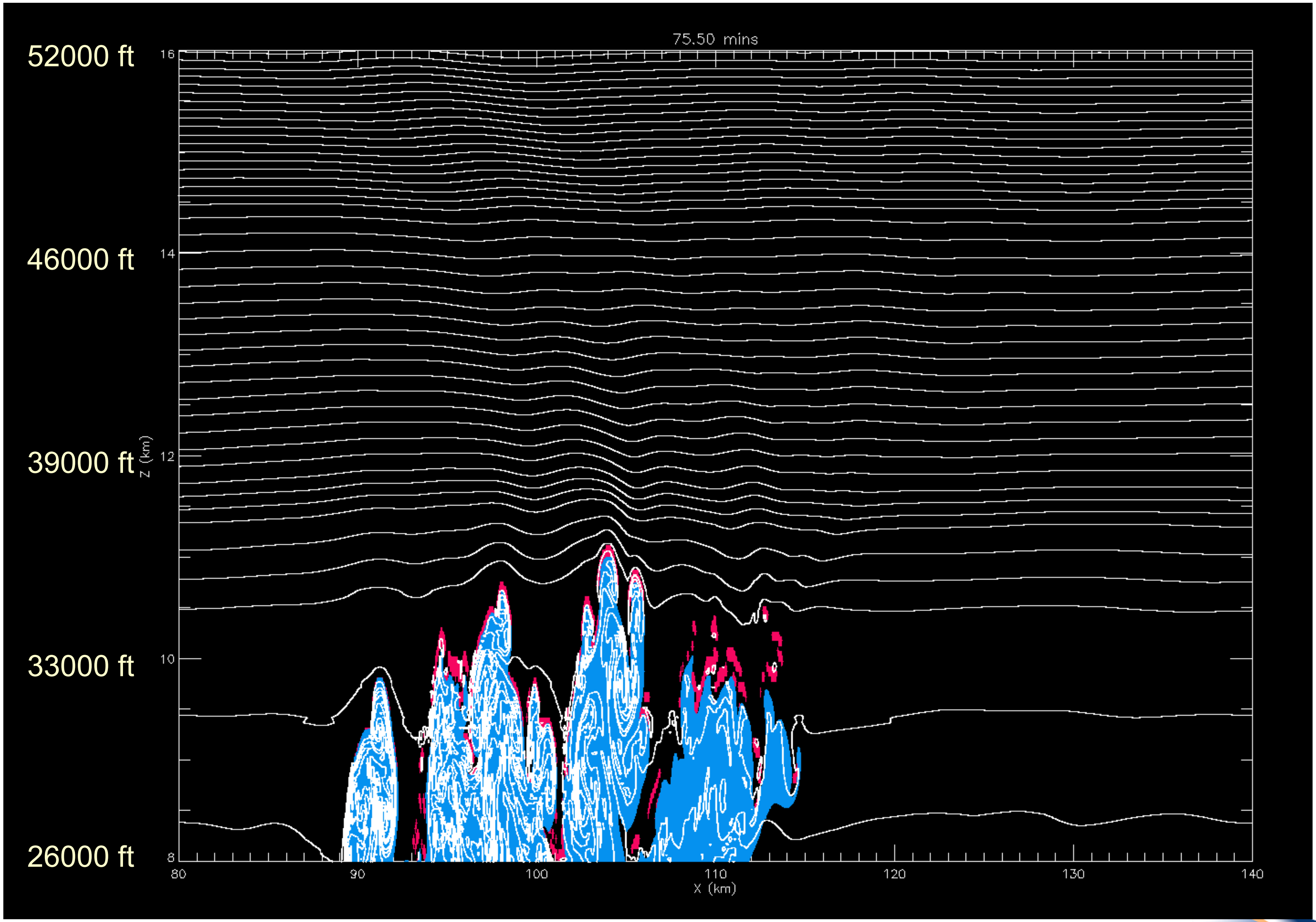
Numerical Simulation: Breaking Internal Gravity Waves and CIT



2-D simulation showing cloud, gravity waves, and turbulence (courtesy of Todd Lane)

Lane, Sharman, Clark, and Hsu (J. Atmos. Sci., 20

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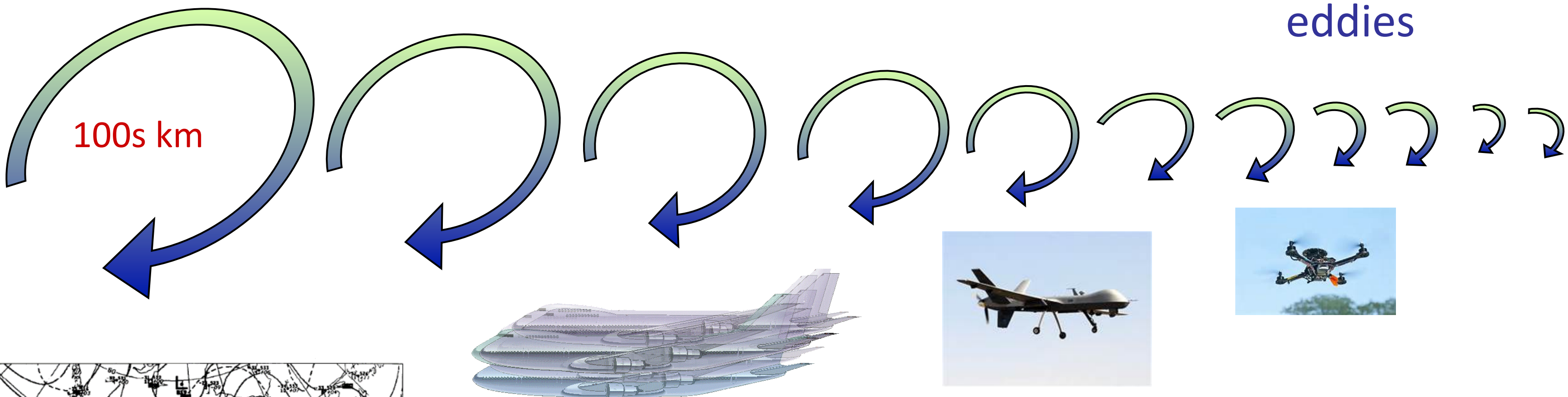
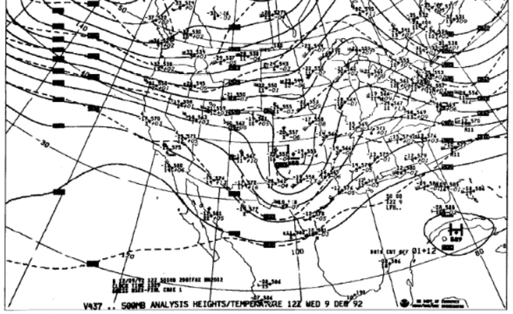
Background - Scales of aircraft turbulence

Largest eddies

“turbulent eddies”

smallest eddies





Commercial aircraft respond to scales from ~100m – 3 km

Note: At upper levels eddies have “pancake”-like structure

NWP resolution

Mesoscale model resolution

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Approach

- No option to directly forecast globally at say 25 m grid spacing
- Since must be operational, must use operational NWP model (e.g., WRF-RAP, HRRR, GFS)
- Available NWP turbulence parameterizations don't work very well, esp. at upper-levels
- Instead, compute "turbulence diagnostics" (D) from NWP output
- Assumes linkage between NWP resolvable scales and aircraft turbulence scales
- Ds are typically related to model spatial variations

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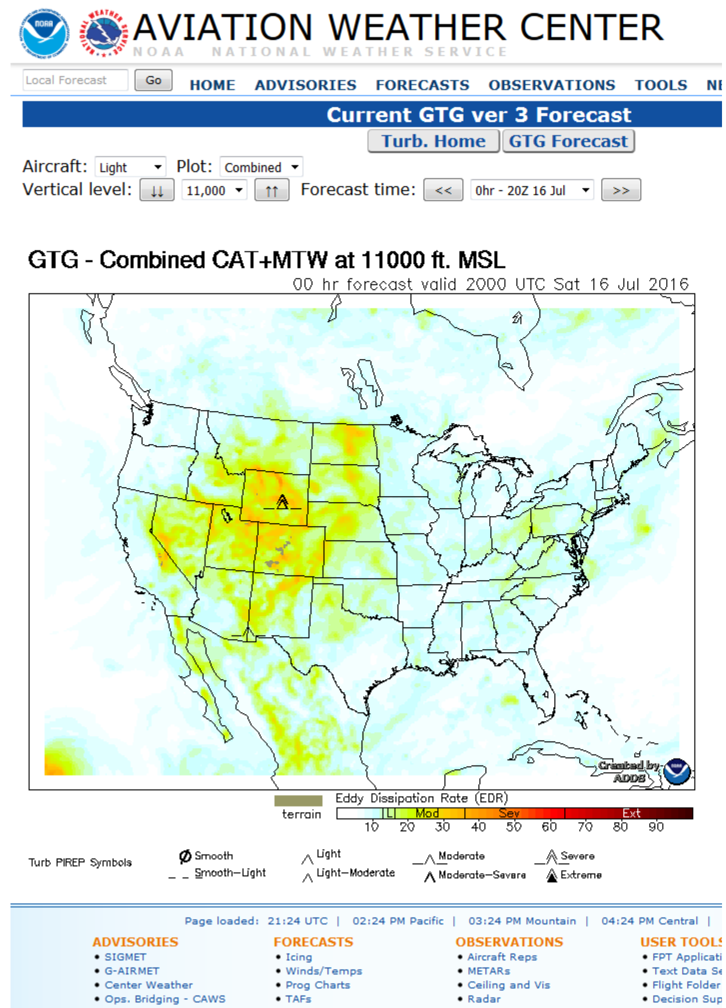
Turbulence Forecasting: Automated Approach*

- Forecast system is called the Graphical Turbulence Guidance (GTG)*
  - Supported by FAA AWRP
  - Currently operational and available 24x7 on Operational ADDS (http://aviationweather.gov/adds)
  - Uses WRF-RAP NWP model
  - Updated hourly
- Computes suite of turbulence diagnostics (D)
- Scale each diagnostic to common intensity measure (D*)
- GTG = ensemble weighted mean

$$GTG = W_1D_1^* + W_2D_2^* + W_3D_3^* + \ldots.$$

- Ws and Ds are turbulence source and altitude dependent



*Sharman et al. Weather & Forecasting 2006

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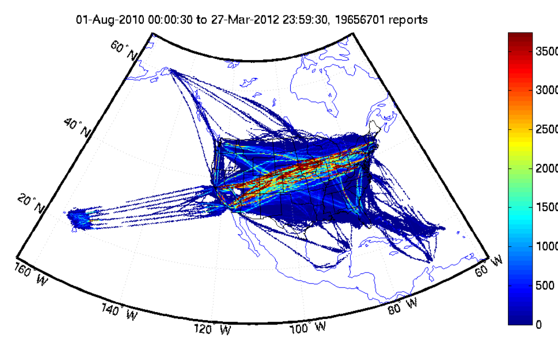
But what are we forecasting?

- "Aircraft scale" eddies that affect aircraft
- Aircraft response is aircraft <u>dependent</u>: "light", "moderate", "severe"
- CANNOT forecast these levels for every aircraft in the airspace
- Instead need atmospheric turbulence measure (i.e. aircraft <u>independent</u> measure)
  - We forecast EDR (= $\varepsilon^{1/3}$ $m^{2/3}s^{-1}$)
    - Convenient 0-1 scale
    - ICAO standard
      - EDR thresholds for mid-sized aircraft are ~ 0.10, 0.3, 0.5 for "light", "moderate", "severe", resp.
    - Can relate to aircraft loads ($\sigma_g \sim \varepsilon^{1/3}$)
    - Can be compared to in situ EDR estimates onboard some commercial aircraft (~400)



UAL B757 insitu EDR Reports ~1.5 yrs

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Conversion of diagnostics to EDR

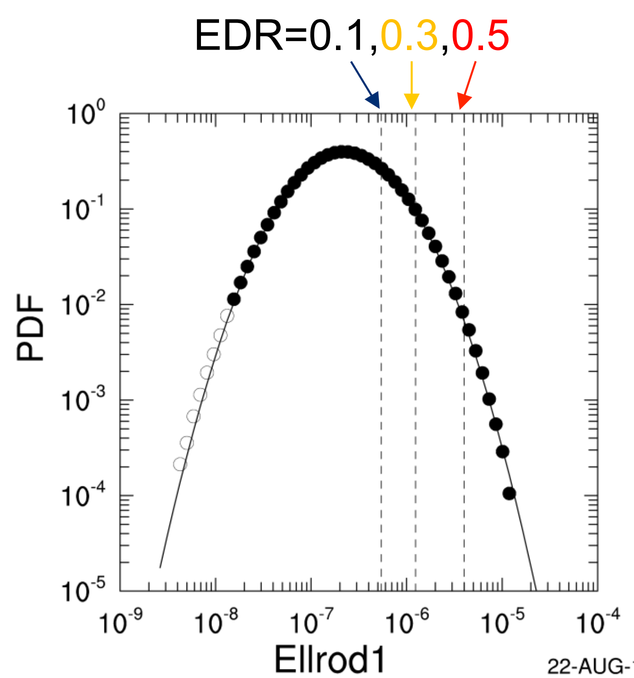
- Each D is rescaled to an EDR assuming a log-normal distribution of edr

$$\log D^* = a + b \log D$$

- Where a and b are chosen to give best fit to expected log-normal distribution and depend on climatology
- Can then combine

GTG (EDR) = $W_1 D_1^* + W_2 D_2^* + W_3 D_3^* + \ldots$

- Tune to get the best set of diagnostics and weights based on comparisons to observations



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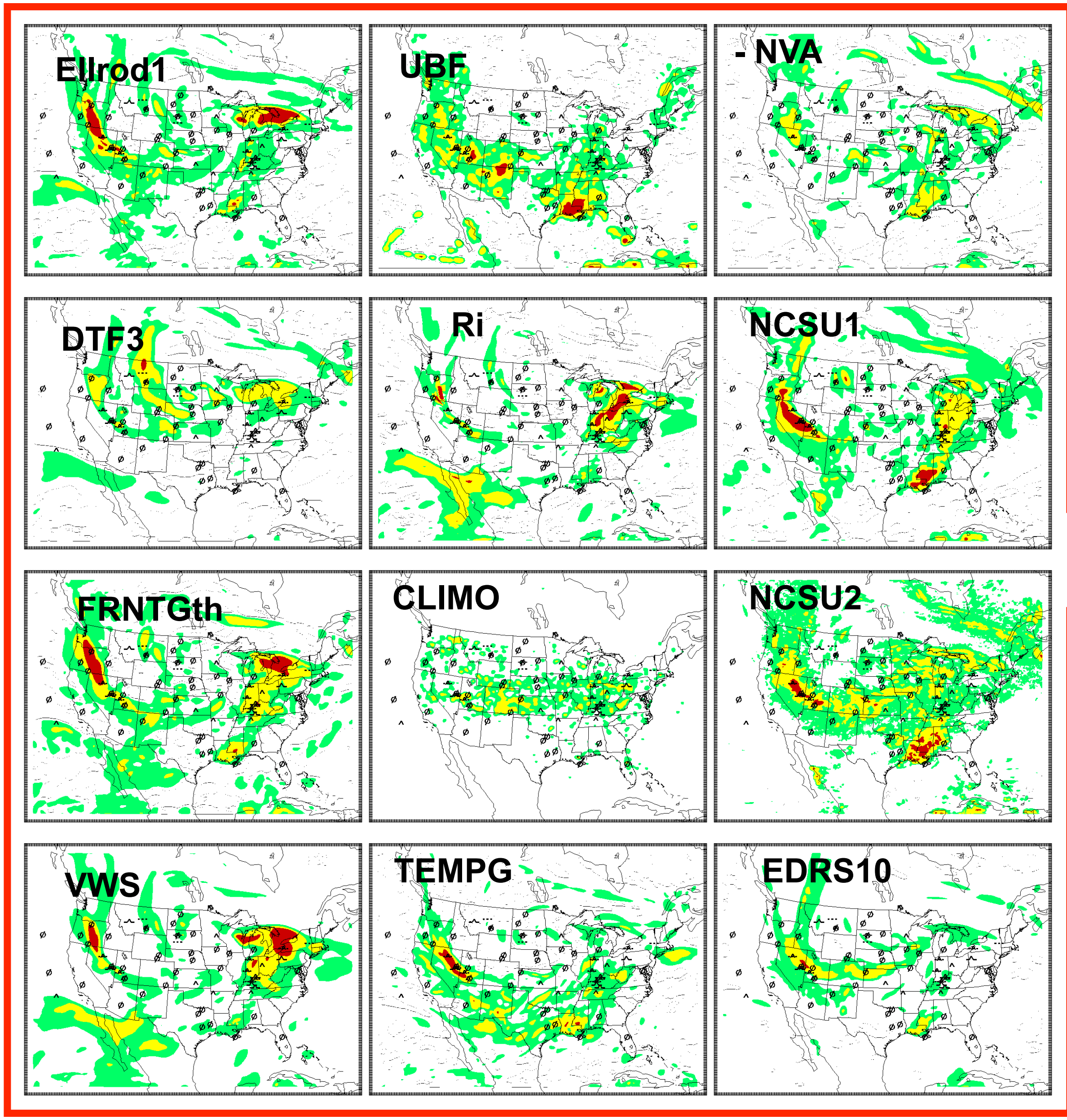
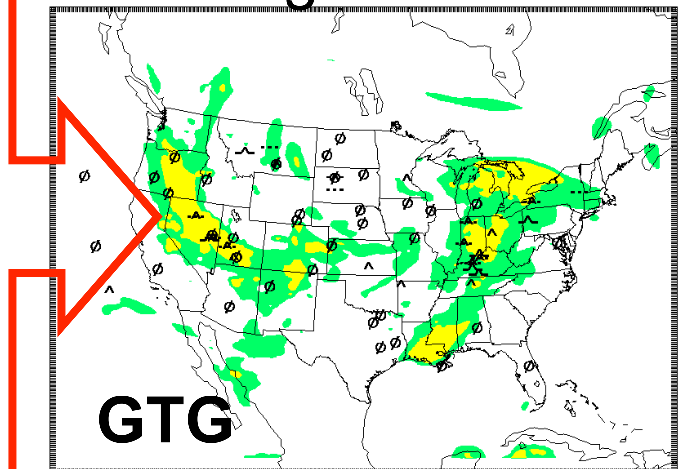


Final Step:
Produce Weighted ensemble of turbulence diagnostics



0 h forecast valid at 22 Sep 2006 15Z

GTG tuning

- GTG produces EDR which is supposed to be aircraft independent
- But selection of diagnostics and weights depends on comparisons to observations
  - These observations are mainly available at upper levels not in the boundary layer
  - The observations are from relatively large aircraft (compared to UAVs)
  - The PBL contains different source/types of turbulence
- So GTG has not been designed/optimized for PBL turbulence and a modified approach is required to better support UAV operations
  - Use verified LES to test diagnostics most suitable for GTG PBL forecasts
  - Domingo…

Upper-level vs. ABL turbulence

Upper-level turbulence

Quasi-two-dimensional in essence

Depends on meteorology

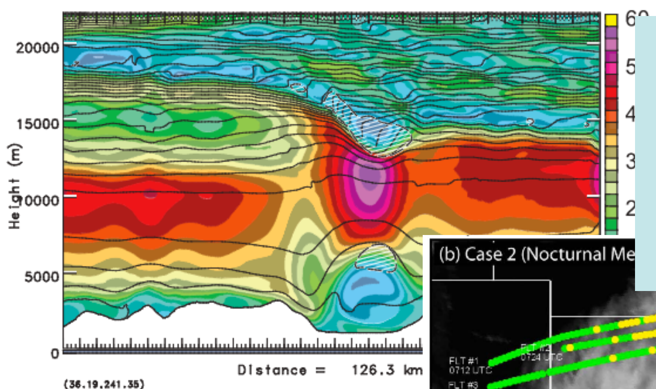
- Strong wind shear (jet streams, upper-level fronts), mountain waves, near-cloud turbulence [*Clear-Air Turbulence*]
- Thunderstorms and clouds

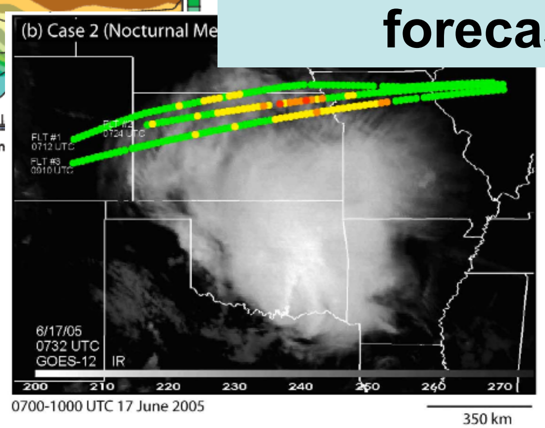
ABL turbulence

Three-dimensional

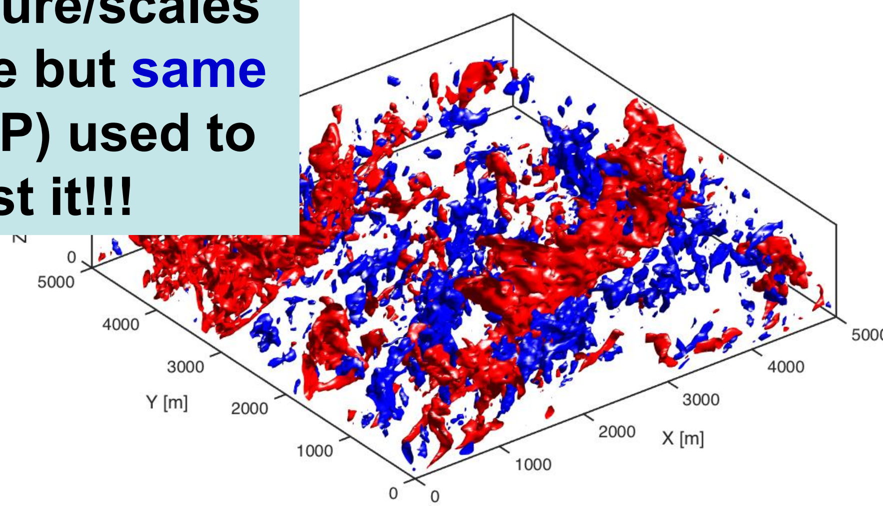
ALWAYS present

- Surface friction
- Stronger during day than nighttime
- Decreases with height
- Enhanced by complex terrain & other heterogeneities (e.g. buildings)





Different nature/scales of turbulence but **same** models (NWP) used to forecast it!!!



Examples taken from Sharman et al. GRL2012

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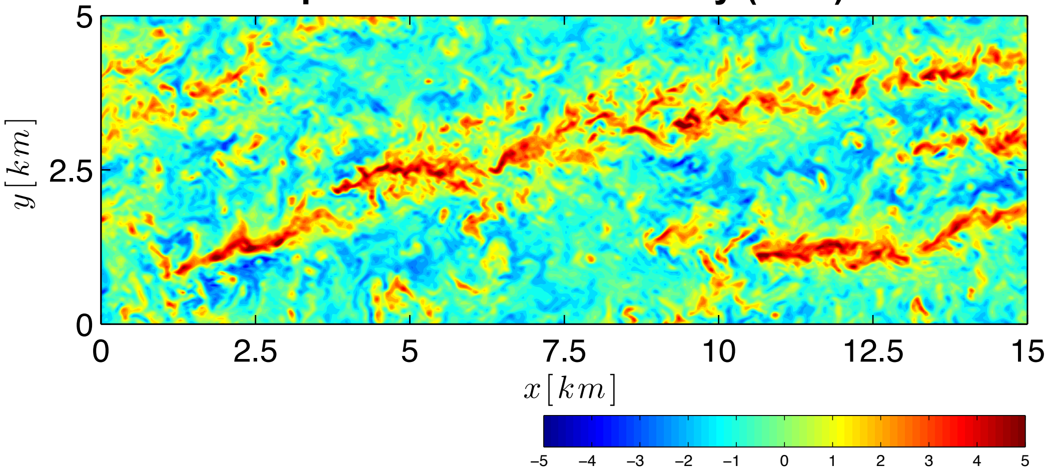
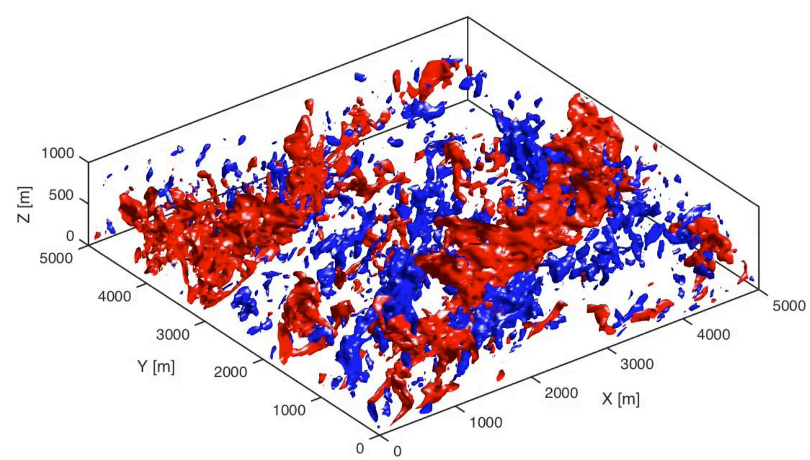
“Idealized” ABL with large-eddy simulations

- Atmospheric state influences turbulence levels in the ABL
- Forecasts deviations will introduce errors in turbulence estimations that are very difficult to quantify
- Use “idealized” large-eddy simulation (LES, dx=20m) -> “reference” ABL

Horizontal plane of vertical velocity (ms^{-1}) at z=400 m



Isosurfaces of vertical velocity [+1.4 ms^{-1} (red), -1.4 ms^{-1} (blue)]



<u>Simulation details</u>

15 km x 15 km x 2 km (3D domain)

Flat terrain

Constant heating of 83 Wm^{-2}

Constant geostrophic wind of 20 ms^{-1}

(Controlled ABL)

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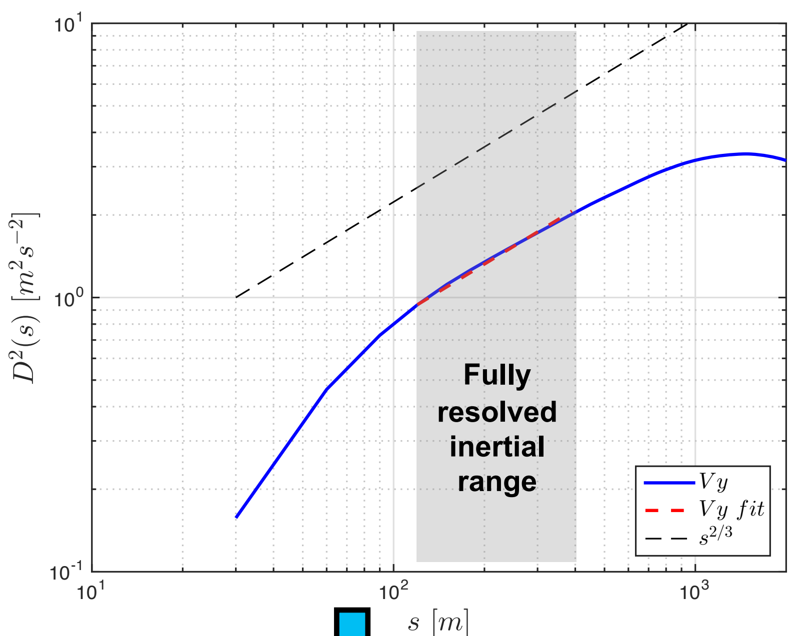
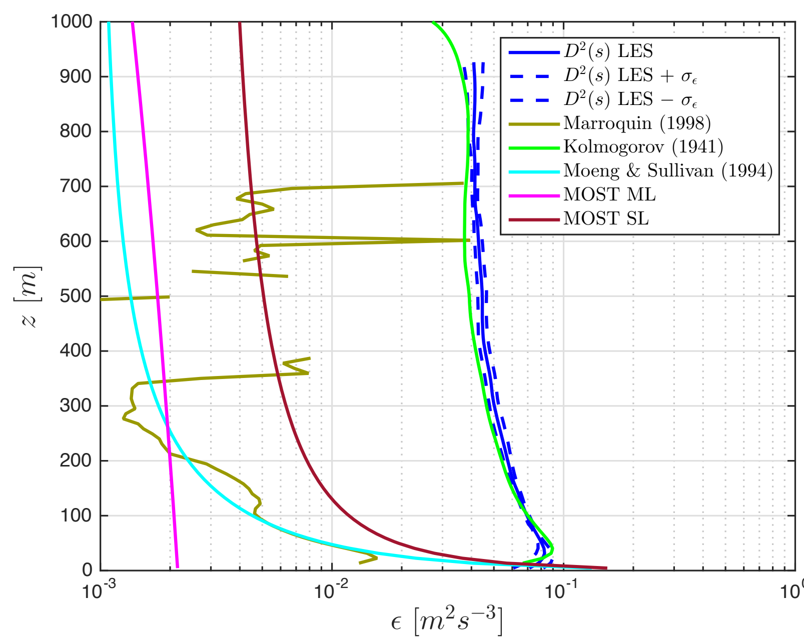
“Idealized” ABL with large-eddy simulations

- Atmospheric state influences turbulence levels in the ABL
- Forecasts deviations will introduce errors in turbulence estimations that are very difficult to quantify
- Use “idealized” large-eddy simulation (LES, dx=20m) -> “reference” ABL
  - Resolved turbulence from the LES provides “true” measurements
  - “Exact” NWP forecast -> horizontally-averaged LES (velocity, TKE, temperature,…)





Kolmogorov (1941)

$$D^2(s) = C_K \varepsilon^{2/3} s^{2/3}$$

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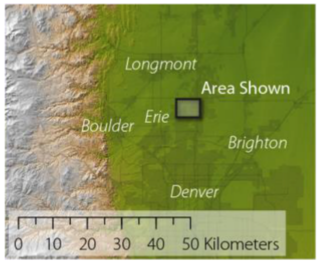
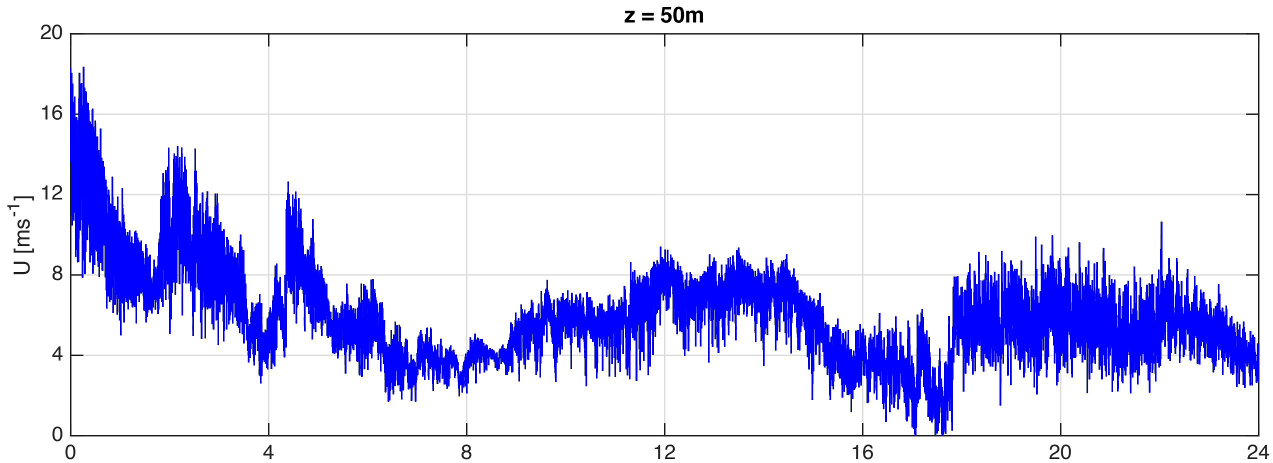
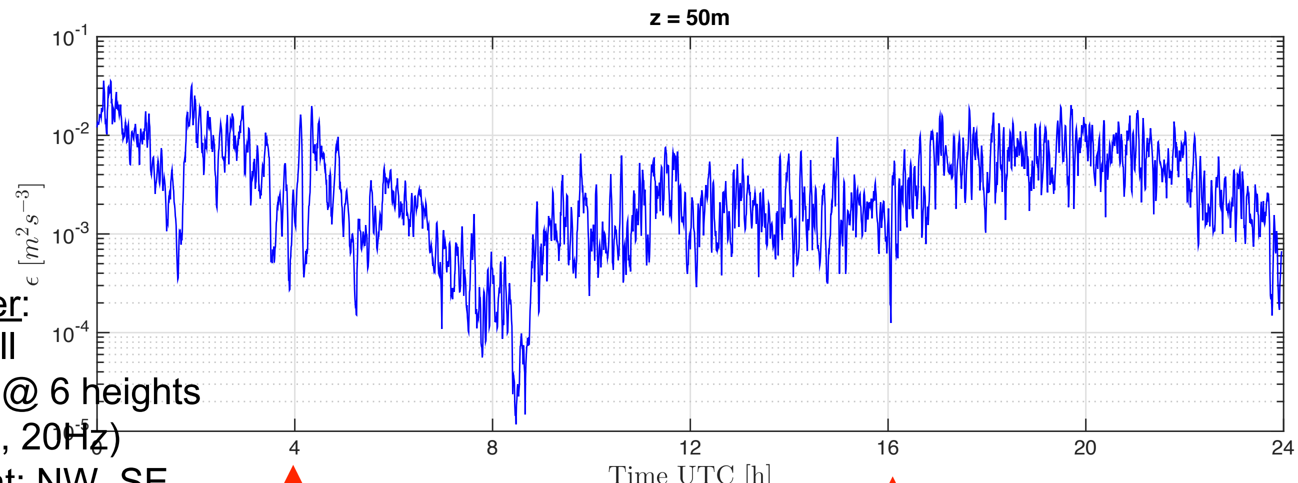
“Real” ABLs: the XPIA field campaign

- The e**X**perimental **P**lanetary boundary layer **I**nstrumentation **A**ssessment campaign took place in March-May 2015 near Boulder, CO (Lundquist et al. 2016)







<u>BAO tower</u>:
300 m tall
Sonic anemometers @ 6 heights
(z=50:50:300m, 20Hz)
2 sonics per height: NW, SE
Additional small tower near by
(sonic @ z=5m, 10Hz)

10 pm

10 am

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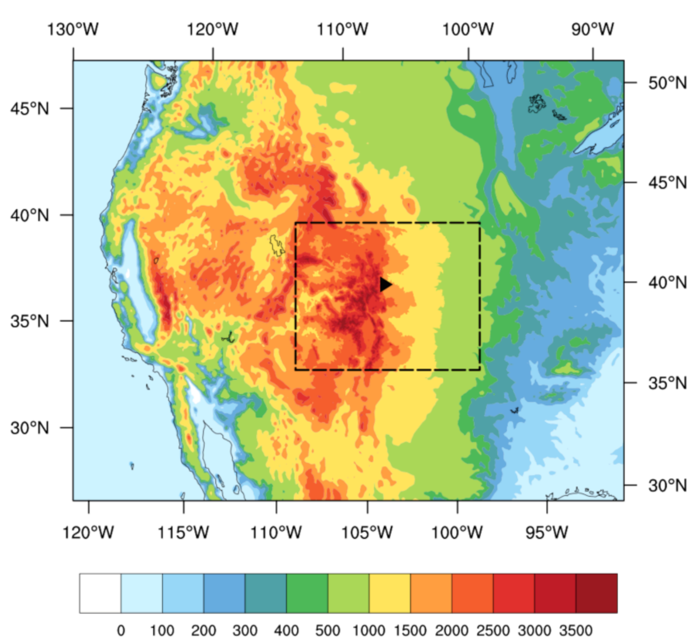
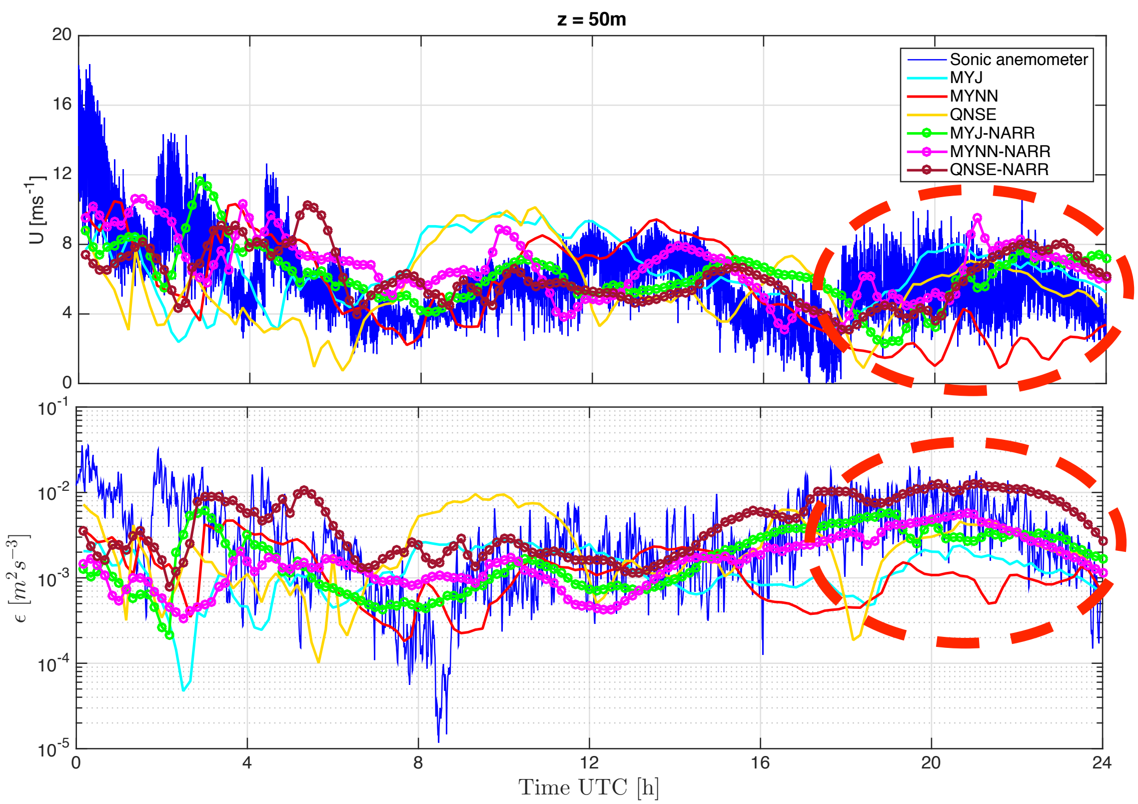
Forecasting EDRs within the ABL

- We are conducting WRF mesoscale simulations (6 configurations) to compare forecasted EDRs to BAO tower observed turbulence (1 month period, March 2015)



<u>Domain1:</u> dx=dy=9km
<u>Domain2</u>: dx=dy=3km
Vertical grid: 73 levels
(40 levels within first 2 km AGL)
3 PBL schemes
2 reanalysis



For UAVs to fly beyond line of sight ->
forecast verification should go beyond wind speed
(ABL structure, stability, terrain…)

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Forecasting EDRs within the ABL

"Idealized" LES has allowed us to identify the best diagnosing criteria to estimate EDRs within the CBL (daytime conditions)

<u>Current and future work</u>

- Analyze NWP model derived EDRs to parameterization of ABL turbulence and reanalysis
- What is the interplay between stability, wind & terrain effects?
- Do the models capture it correctly?

- Implement this approach to forecast ABL EDRs in the GTG algorithm for operational purposes
- Testing of GTG-ABL using HRRR data for XPIA campaign
- Improvements/optimizations to the GTG-ABL algorithm

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